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TRAJECTORY DESIGN FOR A SPACECRAFT CAPABLE OF DEPLOYING PROBES TO THE MARTIAN SURFACE EN ROUTE TO LOW MARS ORBIT

Anthony L. Genova*, Dylan Morrison-Fogel†,

Andres Dono Perez‡, & Alan M. Cassell¶

The presented trajectory design and analysis was performed for the *Aeolus* spacecraft mission concept. The Aeolus spacecraft consists of an orbiter (i.e., "mothership") with the goal of transferring from Earth to low Mars orbit via propulsive and/or atmospheric braking (i.e., aerobraking). During various phases of flight from hyperbolic approach of Mars through low Mars Orbit, the Aeolus orbiter will deploy multiple probes which are targeted to land on the Martian surface with the goal of achieving global surface coverage.

INTRODUCTION

This paper presents the trajectory design and analysis for the Aeolus spacecraft, which plans to deploy multiple probes during various flight phases leading to low Mars orbit insertion.

A total of 24 mission scenarios are considered which included variations on the flight phase of the probe(s) deployment (e.g., deployment during hyperbolic approach phase only vs. deployment during multiple flight phases), type of heliocentric cruise (e.g., type I or II vs. type III or IV), and the type of orbit braking (e.g., propulsive vs. aerobraking). In all 24 mission scenarios (see Appendix A for variations in concept of operations), the deployed probes are targeted to yield global coverage on the surface of Mars as specified by 20 regions with equal diameters of 1,400 km; however, not all architectures achieve global coverage (e.g., due to landing error ellipses with diameter larger than that of a single region). In all scenarios, the Aeolus orbiter enters a high-inclination low Mars orbit (400 km altitude and zero eccentricity) that enables science operations for a period of two Earth years. Due to the quasi-frozen nature of the science orbit considered, at least 50 Earth years is spent in low Mars orbit (with an altitude that remains above 350 km) which satisfies disposal and planetary protection requirements.

Details of the trajectory designs considered for all 24 mission scenarios are presented herein.

* Astrodynamicist, Mission Design Center, Spaceflight Division, NASA Ames Research Center, Moffett Field, CA

† Flight Dynamics Analyst, Millennium Engineering and Integration Co., NASA Ames Research Ctr.., Moffett Field, CA

‡ Flight Dynamics Lead, Mission Design Center, Millennium Engineering and Integration Co., NASA Ames Research Center., Moffett Field, CA

¶ Deputy Chief, Entry Systems and Technology Division, NASA Ames Research Center, Moffett Field, CA
¶ Lead (Acting), Mission Design Center, Spaceflight Division, NASA Ames Research Center, Moffett Field, CA

SOFTWARE TOOLS, ASSUMPTIONS & CONSTRAINTS

The primary software tool used for the presented trajectory analysis was *STK/Astrogator*, which utilized an 8th/9th order Runge-Kutta numerical integrator for orbit propagation within a force model that included an N-body gravity field (50X50 Earth and Mars gravity field and point masses for all other planets), thermal and solar radiation pressure, and atmosphere models at both Earth (Jacchia-Roberts) and Mars (GRAM). Other software analysis tools used included: *Trajectory Browser* (for heliocentric transfer trajectory optimization) and *MATLAB* (for Monte Carlo analysis of probe deployment and dispersion trajectories). Assumptions, constraints, and/or requirements related to the trajectory are listed in Table 1.

Table 1. Assumptions, Constraints, and/or Requirements for the Aeolus Trajectory Design

Category	Assumption, Constraint, and/or Requirement
Launch Timeframe	No earlier than (NET) 2029 and no later than (NLT) 2035
Launch Site	NASA Kennedy Space Center
Launch Energy	Maximum C_3 of the trans-Mars injection < 13 km^2/s^2
Maneuver Modeling	Orbiter uses high thrust-to-mass ratio and impulsive maneuvers within *STK/Astrogator*
Orbiter Wet Mass	Working value of ~3,500 kg, several launch vehicles capable of injecting up to 5,000 kg given maximum C_3 of 13 km^2/s^2
Orbiter Surface Area	Maximum of 20 m^2 exposed to atmospheric drag
Orbiter Coefficient of Atmospheric Drag	2.2
Probe Mass	4.5 kg
Probe Surface Area	0.283 m^2
Probe Coefficient of Atmospheric Drag	1.2
Probe Entry Altitude	120 km
Probe Flight Path Angle	-16 degrees
Probe Entry Velocity	Maximum of 6.1 km/s
Probe-Orbiter Separation Velocity	1 m/s
Mars Surface Regions	20 regions with equal diameter of 1,400 km
Global Surface Coverage	Achieved if all 20 regions contain at least one probe upon landing
Aerobraking Phase Duration	Maximum of one (Earth) year
Aerobraking Altitude	Minimum of 113 km based on *Mars Global Surveyor* mission[1]
Science Orbit	360-degree sweep of Mars longitude within 120 days
Disposal and Planetary Protection	Post-Science Orbit must not impact Mars for at least 50 (Earth) years with high confidence

ALL ARCHITECTURES: HELIOCENTRIC TRANSFER ORBIT CRUISE PHASE

Given the timeframe analysis period of launching NET 2029 and NLT 2035, optimized heliocentric transfers were compiled and extended via the Ames-built *Trajectory Browser* tool with results displayed in Table 2. Two distinct types of heliocentric transfers emerged: type I/II (with duration between ~6 and ~9 months) and type III/IV (duration between ~27 and ~29 months). The maximum C_3 value of all solutions seen in Table 2 satisfy the requirement of maximum C_3 < 13 km^2/s^2. The opportunities in Table 2 yield varying values of solar longitude, L_s, a parameter used to indicate the season on either the northern or southern hemisphere of Mars; thus, L_s is relevant to both the epoch and location of probe landings for purposes of engineering and science (e.g., landing close to a retreating frost line). Finally, the Mars orbit insertion (MOI) maneuver from hyperbolic approach to a 400 km circular Mars orbit is seen to range from ~2,100 to ~2,600 m/s, although this requirement does not have to be met by purely propulsive means; several mission scenarios utilize aerobraking which can reduce the 2,600 MOI ΔV requirement by up to ~1,000 m/s.

Table 2. Optimal Launch Opportunities from Earth (NASA KSC) to Mars (400 km circular orbit) between 2029 and 2035 (extended from *Trajectory Browser* results).

Earth Departure Date	Mars Arrival Date	Solar Longitude, *Ls*, at Mars Arrival (deg)	Cruise (Heliocentric) Duration (months)	Cruise Type (I/II or III/IV)	C_3 of Launch (km^2/s^2)	ΔV of Mars Orbit Insertion to 400 km Circular Orbit
Oct. 2, 2030	Feb. 28, 2033	127.8	~ 29	III/IV	11	~ 2,100
Dec. 21, 2030	Oct. 5, 2031	224.9	~ 9	I/II	10.2	~ 2,600
Oct. 23, 2032	Feb. 18, 2035	144.5	~ 28	III/IV	9.5	~ 2,100
April 17, 2033	Oct. 26, 2033	265.4	~ 6	I/II	8.1	~ 2,500
Oct. 29, 2034	Feb. 7, 2037	161	~ 27	III/IV	8.4	~ 2,200
June 26, 2035	Jan. 20, 2036	341.2	~ 7	I/II	9.6	~ 2,200

For purposes of presentation and for exploring probe deployment options after achieving MOI, the type I/II transfer with earliest launch date in Table 2 is selected which serves to bound the required MOI ΔV and thus propellant mass needed for a specific spacecraft design. The corresponding launch date of analysis is adjusted from Dec 21, 2030 to Dec. 31, given the latter bounds the required MOI ΔV for this type I/II transfer in calendar year 2030. After TMI on Dec. 31, 2030, the Aeolus orbiter and stowed probes coast for 9 months before reaching Mars. However, certain mission scenarios (i.e., *Architecture 1* and associated hybrid architectures) begin deployment operations of probes one month before closest approach of Mars, in the hyperbolic approach phase (explained in more detail in the next section). In all scenarios, the MOI maneuver is performed at Mars close-approach on/near Oct. 5, 2031 (Fig. 1), which requires ~2,600 m/s of ΔV to reach the 400 km circular science orbit.

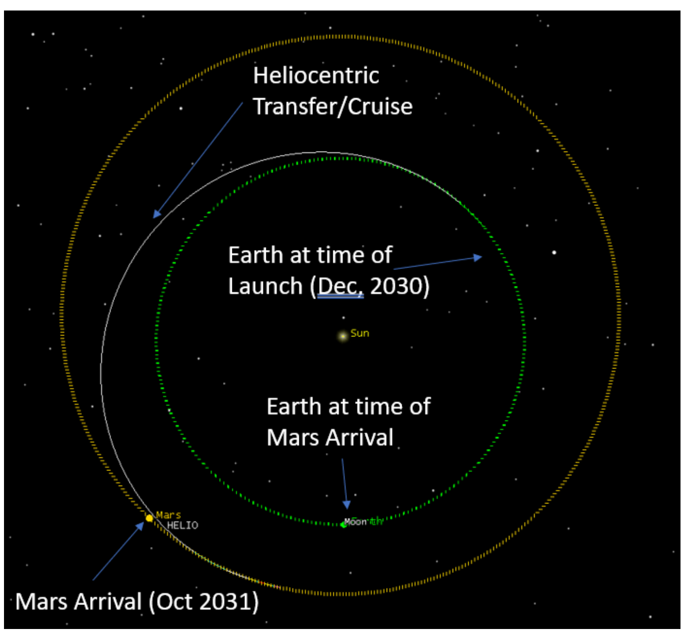

Figure 1. Optimized heliocentric transfer: Earth launch in Dec. 2030 and Mars arrival in Oct. 2031.

To reduce gravity losses due to maneuver burn duration in practice, the MOI maneuver is split into a capture maneuver which requires ~1,300 m/s and achieves a highly eccentric Mars orbit; the remaining ΔV requirement of MOI is performed either via propulsion or aerobraking. The aerobraking phase may last up to one year and is dependent on the spacecraft mass and surface area properties; this phase of flight is focused on in the *Architecture 2* section. Upon completing MOI (and possible deployment of probes via *Architecture 3* and associated hybrids), the Aeolus orbiter will begin its science operations in a 400 km circular Mars orbit that is quasi-frozen with periareion and apoareion altitudes varying from ~350 to ~405 km and ~405 to ~460 km, respectively (Fig. 2).

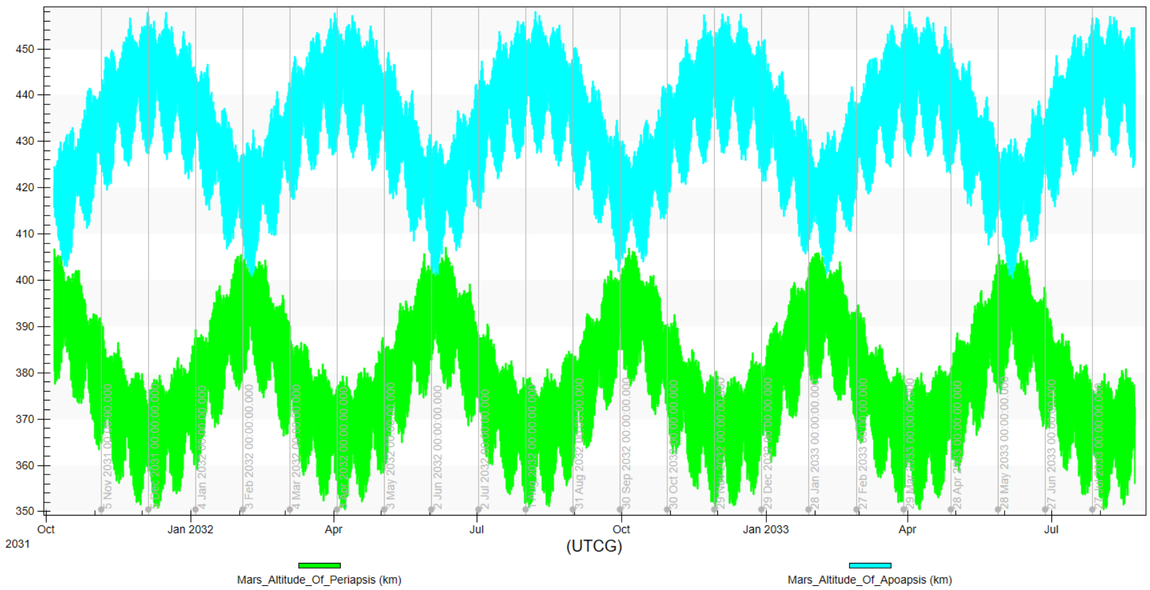

Figure 2. Low Mars orbit altitude begins at 400 km (circular) before oscillating between 350 and 450 km over ~2 Earth years.

The baseline science orbit was selected based on work performed by Ames Research Center[2, 3]. Specifically, the science orbit targets an inclination of 73 degrees such that the requirement of orbit ground track precession of 360 degrees in longitude within 120 days is met; Fig. 3 displays 120-days of ground tracks which shows 360-degrees in longitude precession many times over.

Figure 3. 120 days of Mars ground tracks easily meets the 360-deg longitude sweep requirement.

ARCHITECTURE 1: PROBE DEPLOYMENT FROM HYPERBOLIC APPROACH

Architecture 1 involves the deployment of probes upon hyperbolic approach which precedes the critical MOI maneuver at Mars close approach. Results from a previous Ames study, *PASCAL*[4], indicated that the earliest release of a probe during hyperbolic approach fixed to 30 days prior to MOI ensures a viable landing error ellipse on the Martian surface; for the presented Aeolus study, the earliest deployment was fixed to 25 days before MOI to include margin. The latest a probe is scheduled to be deployed is set to 10 days before MOI to allow sufficient time for the Aeolus orbiter to prepare for the MOI maneuver. Thus, for *Architecture 1*, probes are deployed between 10 and 25 days before the MOI maneuver. Given the nominal number of probes in this architecture is set to 20, a single probe is deployed every 18 hours to allow for a simplified spacecraft deployment operations during hyperbolic approach (Fig. 4).

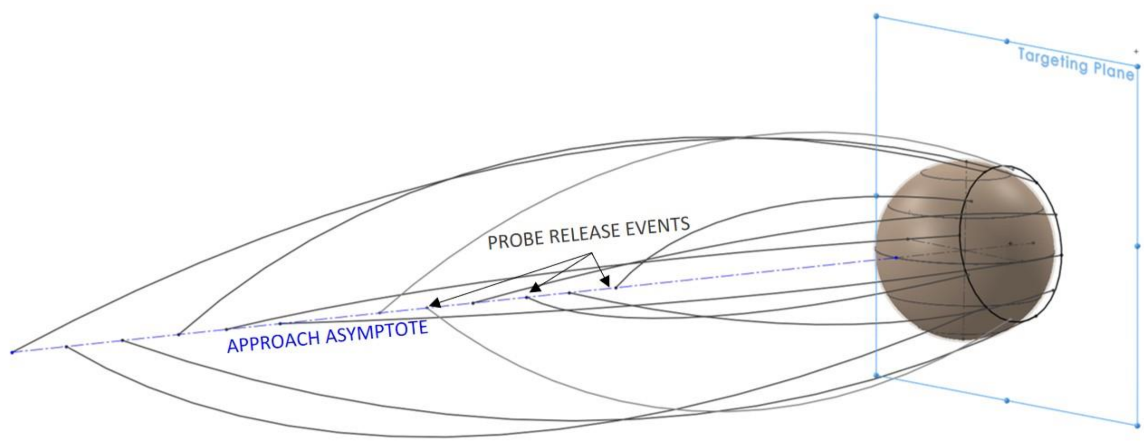

Figure 4. Concept of operations summary for *Architecture 1* which entails deployment of 20 probes (one probe deployed every 18 hours) during hyperbolic approach of Mars, between 10 and 25 days preceding the MOI maneuver.

All probes are targeted to reach a 120 km altitude at Mars (i.e., atmospheric entry corridor) with a flight path angle of 16 degrees; the corresponding entry velocity is ~6.1 km/sec for this nominal case. The orbiter is the sole spacecraft performing maneuvers, which vary the epoch of atmospheric entry for each probe such that Mars rotates with respect to the approximately fixed annulus of the hyperbolic approach asymptote. This effect is visualized in Figures 5-8, which display epochs at Mars over a span of 17 hours (Oct. 6, 2031 from 2:00 to 19:00 UTCG) which is the total time Mars rotates between the first and last probe landing.

For the presented case and value of Ls, the following range of landing latitudes are available: -68 to 42 degrees. The latitude range of inaccessibility depends on the approach asymptote and arrival date, which dictates Mars' axial tilt. For the nominal case with Mars arrival in October of 2031 and Ls = 225 degrees (i.e., autumn in Mars' northern hemisphere), Mars' north pole vector faces toward the spacecraft's hyperbolic approach asymptote direction which enables more southern latitudes to be targeted vs. northern latitudes (Fig. 5).

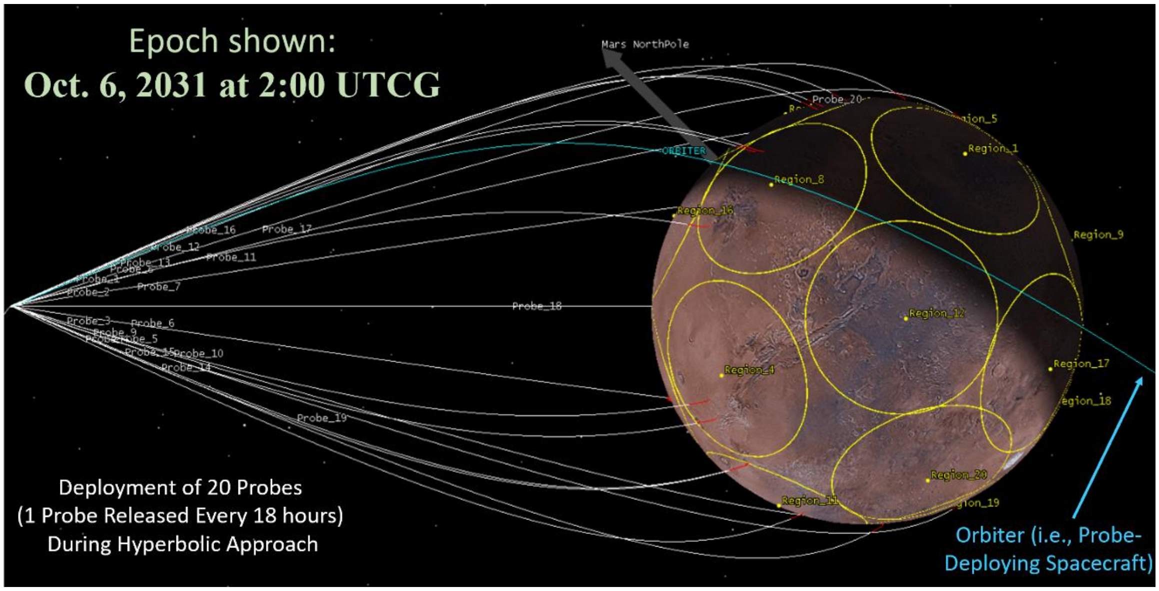

Figure 5. Deployment of 20 probes during hyperbolic approach of Mars (*Architecture 1*) shown at epoch of Oct. 6, 2031 at 2:00 UTCG when the first probe lands (i.e., Probe 20). The Orbiter is also seen shortly before performing the MOI.

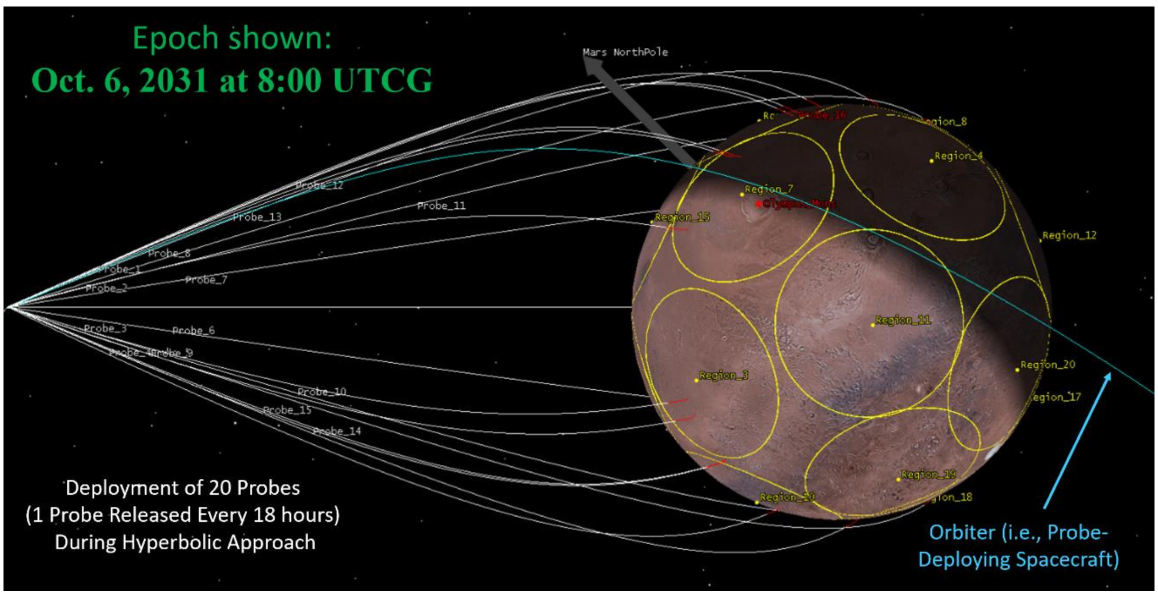

Figure 6. Deployment of 20 probes during hyperbolic approach of Mars (*Architecture 1*) shown at epoch of Oct. 6, 2031 at 8:00 UTCG.

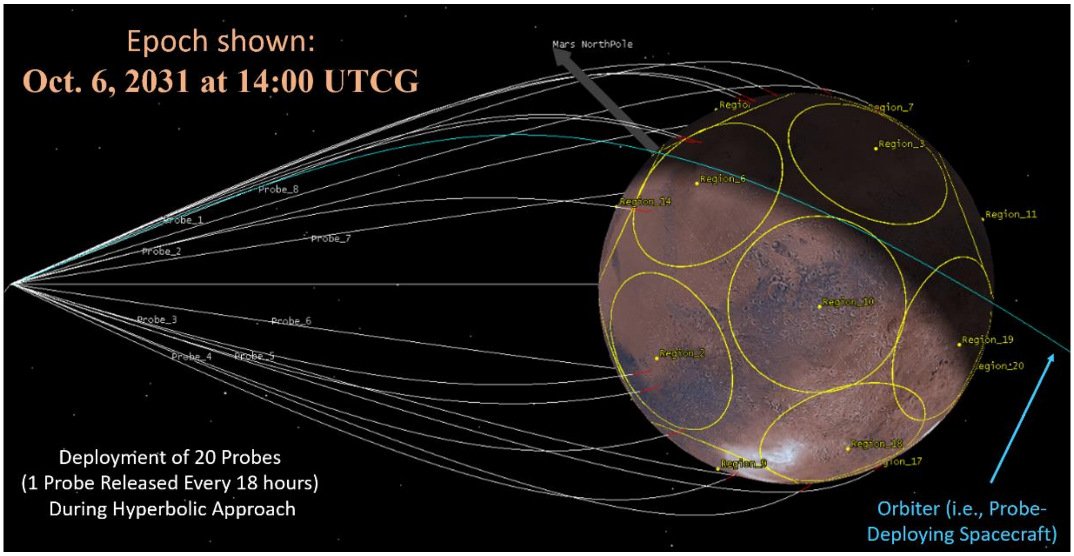

Figure 7. Deployment of 20 probes during hyperbolic approach of Mars (*Architecture 1*) shown at epoch of Oct. 6, 2031 at 14:00 UTCG.

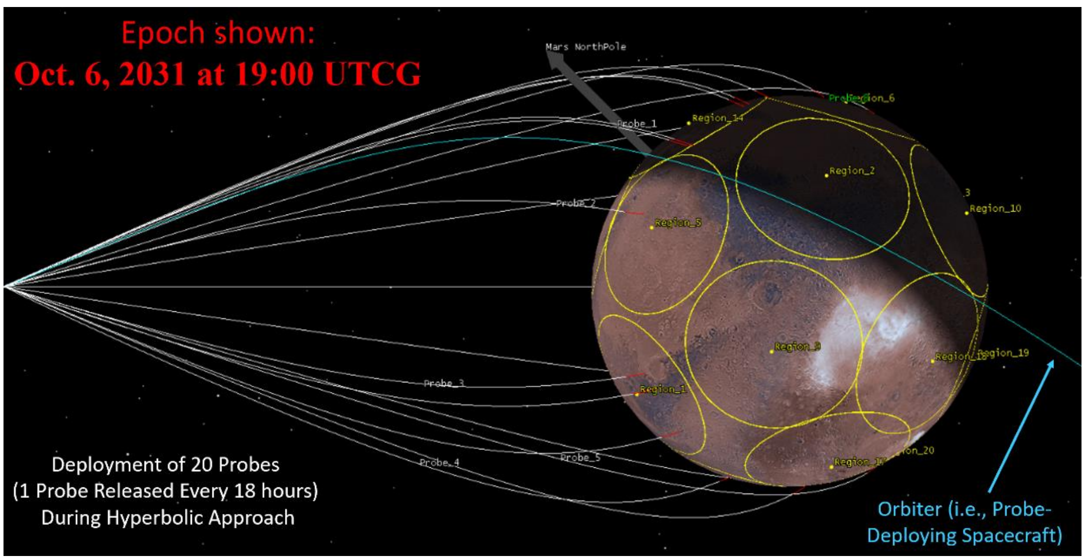

Figure 8. Deployment of 20 probes during hyperbolic approach of Mars (*Architecture 1*) shown at epoch of Oct. 6, 2031 at 19:00 UTCG shortly before the last probe lands (i.e., Probe 1).

Despite the limits in latitude coverage of probe landing sites from hyperbolic approach, all 20 equal-diameter regions are targeted in *Architecture 1* (Fig. 9). The ΔV estimated to deploy each probe is 12.5 m/s (see Appendices B and C for ΔV estimates for end-to-end trajectories utilizing this deployment method). This global coverage is achieved solely from hyperbolic approach; however, it is noted that error ellipses due to deployment dispersions may move the landing sites of these northern-most probes to lower latitudes. However, it will be demonstrated in the next section that *Architecture 2* provides a means of targeting the full range of latitude values; thus, a combination of *Architectures 1* and *2* (i.e., *hybrid Architecture 1 & 2*) can yield more flexibility in targeting latitude regions not accessible by *Architecture 1* alone.

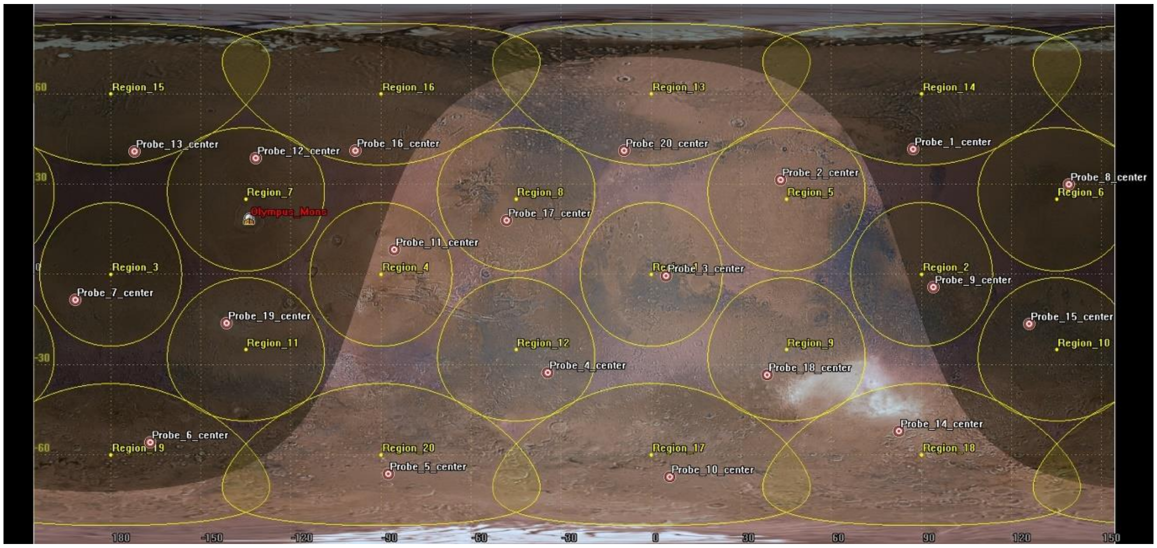

Figure 9. Deployment of 20 probes, targeted to 20 equal-diameter regions on Mars, during hyperbolic approach of Mars (*Architecture 1*).

ARCHITECTURE 2: PROBE DEPLOYMENT FROM ELLIPTICAL ORBIT

Architecture 2 involves the deployment of probes after the MOI maneuver, in an elliptical Mars orbit. The nominal elliptical orbit parameters following MOI include: periapsis altitude = 400 km, apoapsis altitude = 120,000 km, and i = 73 deg, which result in a probe entry velocity of 4.8 km/s at a targeted 16-degree flight path angle. An example deployment of a probe from elliptical Mars orbit is presented in Figure 10, where it is seen that a maneuver at apoapsis by the Aeolus orbiter targets a 16-degree flight path angle at 120 km altitude such that a probe achieves a safe atmospheric entry before reaching its intended landing site. The Aeolus orbiter performs a correction maneuver to ensure it remains in elliptical orbit to prepare for deployment of the next probe.

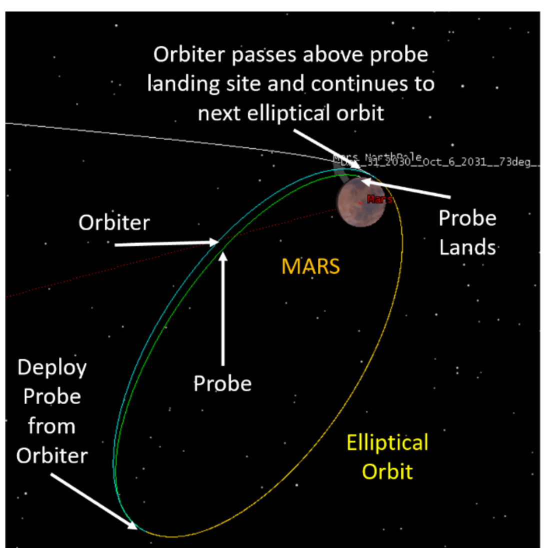

Figure 10. *Architecture 2* deployment of probe by Aeolus orbiter in elliptical Mars orbit.

However, an elliptical Mars orbit contains a fixed apsides which limits surface coverage of probes; thus, a method for rotating the line of apsides is sought. Fortunately, either propulsive braking or aerobraking causes the apsides to rotate which can be used to increase flexibility of *Architecture 2.* Assuming the Aeolus orbiter contains a wet mass of ~1,800 kg at the time orbit braking begins, it is seen in Fig. 11 that the apsides rotates nearly 360 degrees, with apoapsis altitude continuously decreasing, before the orbit becomes circular ($e = 0$). This rotation enables global surface coverage of probes (e.g. see Fig. 12) via careful selection of the timing and targeting of deployment throughout the elliptical orbit phase and/or shortly after achieving $e = 0$; in the latter case the apsides is undefined and thus can be established by choosing the true anomaly of the orbiter's maneuver in circular orbit which re-establishes an elliptical orbit. Of note is that the *Trace Gas Orbiter* spacecraft's aerobraking profile yielded a similar rotation in apsides[5].

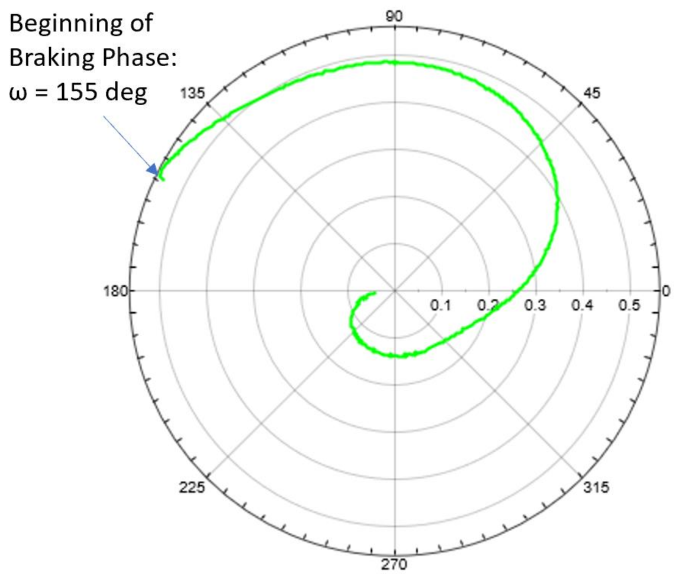

Figure 11. Orbit Evolution: argument of periapsis (ω) and eccentricity (e) evolution during aerobraking (or propulsive-braking) phase. Motion of apsides rotation is clockwise beginning at ω = 155 degrees.

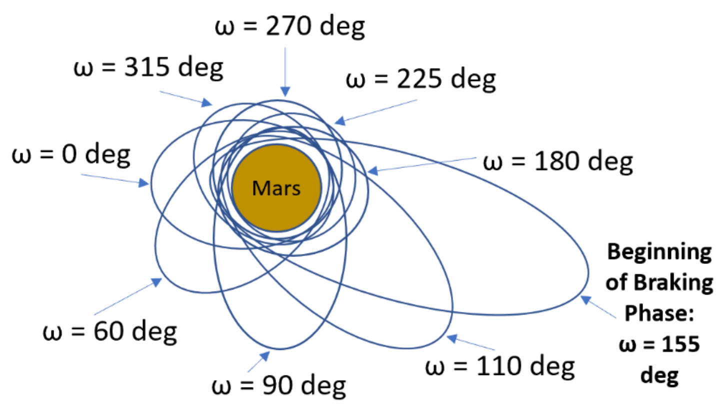

Figure 12. Representative view of line of apsides rotation with decreasing apoapsis altitude in elliptical Mars orbit. Forward-time motion of apsides rotation is clockwise beginning when apoapsis altitude is highest near ω = 155 degrees.

When *Architecture 2* is combined with *Architecture 1* (i.e., *hybrid Architecture 1 & 2*), the elliptical Mars orbit can be used to deploy probes near the pole that was inaccessible from hyperbolic approach. In the nominal case, during the aerobraking phase, the line of apsides crosses near 90 degrees (ω = 110 deg shown in Fig. 13) at which time Mars north pole (e.g., latitude > 65 degrees) at -16 degree flight path angle, and 120 km periapsis altitude can be targeted via a ΔV = 55.8 m/s (by the orbiter) to deploy a probe and then ΔV = 65 m/s to divert (again by the orbiter, to ensure it remains in elliptical orbit). Although landing sites exactly at a pole (latitude = 90 or -90 degrees) is possible via this method, concerns of landing in frost exist; thus, a latitude of 66.3 degrees is chosen as the maximum (northern) latitude of a probe landing site given Mars' season in the northern hemisphere upon landing (L_s = 314 degrees).

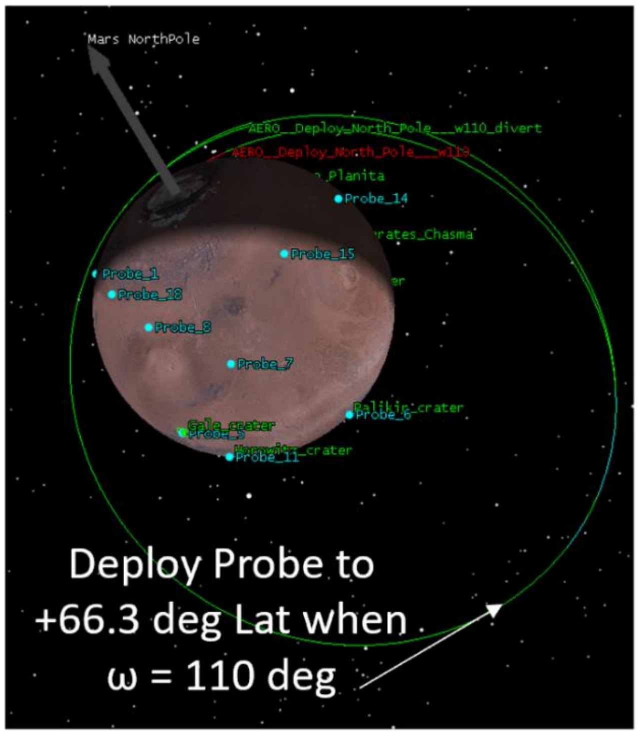

Figure 13. ***Architecture 2*** **deployment of probe in northern latitude region. Periapsis altitude upon atmospheric entry = 120km and V_{mag} = 4.3 km/s. At time of deployment, the elliptical orbit parameters include: ω=110 deg, apoapsis altitude = 8,200 km. At time of landing, the latitude = 66.3 degrees and solar longitude (L_s) = 314 degrees.**

A summary of the ConOps inherent to *Architecture 2* is presented in Fig. 14, which assumes the apsides of the elliptical orbit is rotating upon reaching circular orbit via propulsive braking or aerobraking. Note that the ΔV estimated to deploy each probe is 25 m/s; see Appendices B and C for ΔV estimates for end-to-end trajectories utilizing this deployment approach.

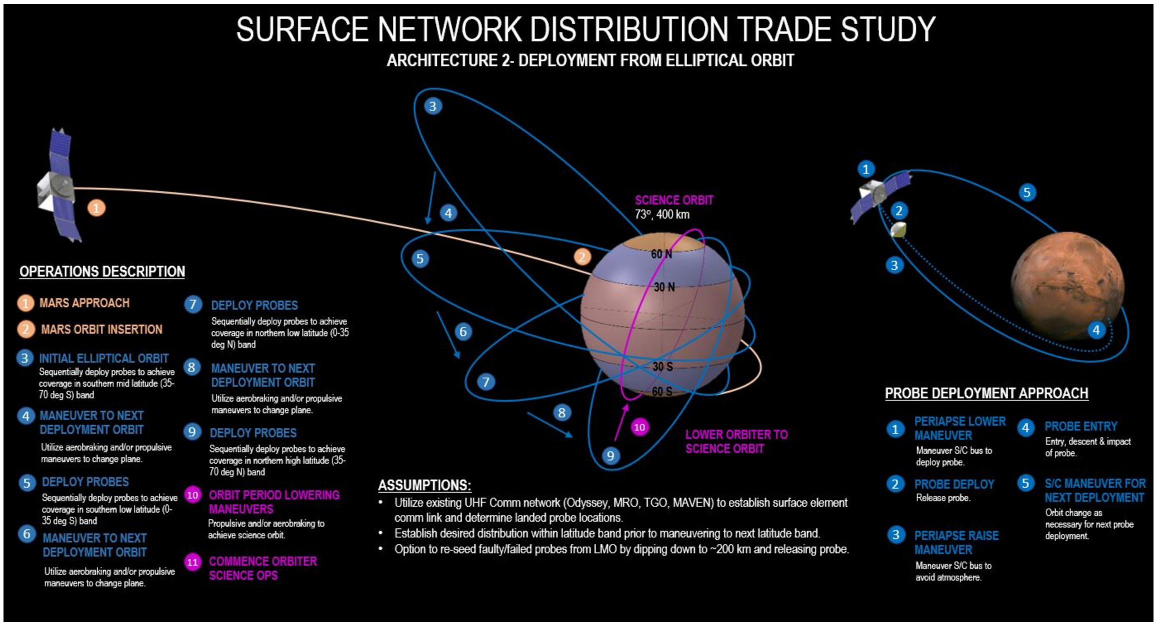

Figure 14. Concept of operations summary for *Architecture 2* which entails deployment of 20 probes throughout the elliptical orbit phase, which begins shortly after MOI.

A detailed ΔV budget for *Option 17* is presented in Table 3, given its selection as the nominal mission architecture and hybrid nature which reveals elements of both *Architectures 1* and 2 (see Appendix C). Note that ΔV budgets in Appendices B and C include allowances for finite burn losses (MOI), aerobraking trim maneuvers to maintain periapsis altitude, transfer to a safe haven orbit to survive a possible solar conjunction, orbit resonance adjustments (if needed), contingency maneuvers (5% of deterministic ΔV total), and trajectory correction maneuvers (TCMs).

Table 3. Detailed ΔV Budget for Hybrid Architecture 1 & 2 (Option 17).

Maneuver(s) Description	**ΔV Calculated or Allocated**
Deployment of (20) Probes during Hyperbolic Approach of Mars	250 m/s
Divert by Orbiter to target MOI conditions	7.2 m/s
MOI to capture into Mars orbit with 120,000 km apoapsis altitude	1,280 m/s
Finite Burn Losses during MOI	64 m/s
Deployment of (4) Probes in Elliptical Mars Orbit	100 m/s
Follow-up Orbit Braking to reduce duration of Aerobraking phase	273.7 m/s
Aerobraking trim maneuvers to maintain periapsis altitude	36 m/s
Safe haven Orbit to survive Solar Conjunction period	50 m/s
Walk-out of Aerobraking phase to enter Science Orbit	74 m/s
Science Orbit Resonance Adjustment Maneuvers	25 m/s
Contingency (5% of deterministic total)	104.8 m/s
Trajectory Correction Maneuvers	80 m/s
TOTAL	**2,344.7 m/s**

ARCHITECTURE 3: DEPLOYMENT of PROBES FROM LOW MARS ORBIT

Probe deployment from a near-circular low Mars orbit increases reseeding opportunities and reduces atmospheric entry velocity. *Architecture 3* considers the probe deployment mechanism to be mechanical, providing a separation ΔV of 1-3 m/s. Given this relatively low separation ΔV, additional ΔV by means of atmospheric braking is considered. The Aeolus spacecraft is held in its science orbit at an altitude of 400 km, then lowering to an altitude of 200 km for the probe separation phase (see Figure 15). Subsequently, probes are confirmed to be active in their respective regional targets (see Figure 16) otherwise necessitating reseeding deployments to compensate. Once probe communication links are active, the spacecraft is raised to its science orbit altitude of 400 km for nominal science phase to begin.

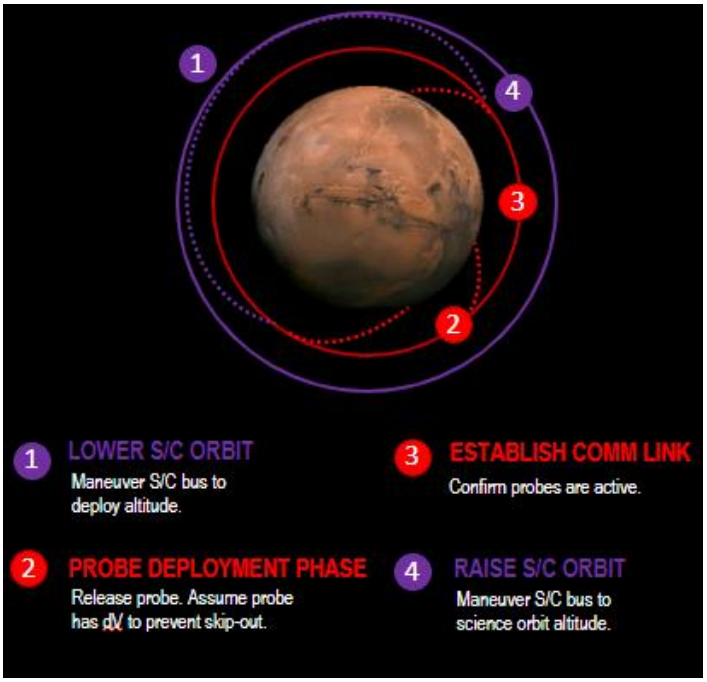

Figure 15. *Architecture 3*: Probe deployment from low Mars orbit, which begins shortly after orbital braking is completed in elliptical Mars orbit, with reseeding opportunities immediately following communication link survey.

Martian atmospheric drag is considerable below an altitude of 170 km, hence the selection of a 200 km probe deployment altitude. Affixed to atmospheric perturbations is a non-uniform gravitational well caused by the asymmetric and heterogeneous mass distribution of Mars. The combination of these two factors results in gradual orbit decay of the main spacecraft, eventually causing the spacecraft to reach a periapsis altitude of 170 km. Two probe deployment cases are considered; one which deploys probes at periapsis altitude ≤170 km and another which deploys probes at apoapsis following a periapsis altitude ≤170 km. The Mars Global Atmospheric Model 2010 (GRAM2010) used within the propagator until reaching an interface altitude of 120 km, at which higher fidelity entry, descent, and landing simulations are performed with NASA's TRAJ tool. Seen in Figure 16, the duration of main spacecraft orbit decay from 200 km to 170 km is ~17.5 days and the subsequent probe separation to 120 km interface is ~4.25 days. Figure 17 similarly illustrates a main spacecraft orbit decay of ~17.5 days now with subsequent probe separation to 120 km interface is ~7 days.

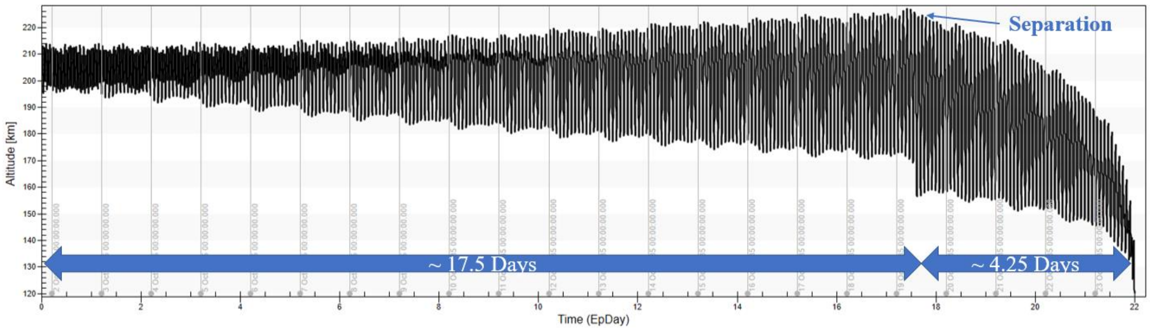

Figure 16. Probe altitude trend prior-to and post- 3 m/s separation at apoapsis following periapsis altitude dip ≤ 170 km.

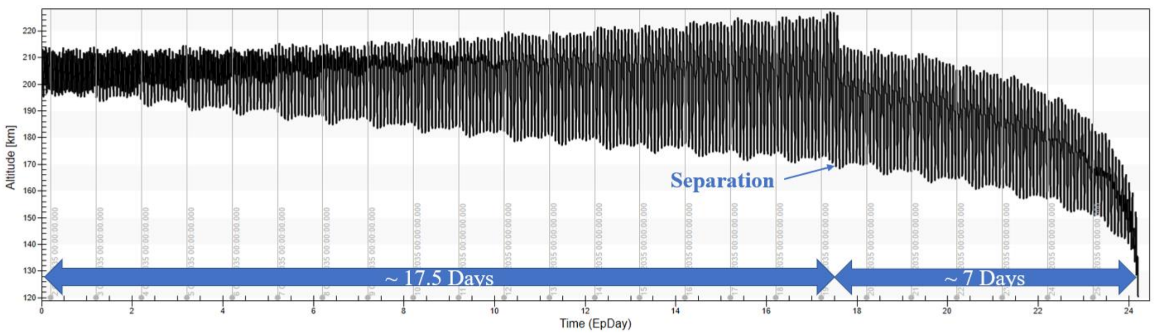

Figure 17. Probe altitude trend prior-to and post- 3 m/s separation at periapsis altitude ≤ 170 km.

Being initially of near-circular orbit and having little surface area to produce dominant drag, the post-separation probe descent covers 25-35 orbits prior to a 120 km interface altitude (pre-separation and post separation orbits shown in Fig. 18). Probe entry velocities at interface for *Architecture 3* are ≤ 3.5 km/s with a horizontal flight path angle of approximately -2°. Under *Architecture 3,* 18 or more probes can be released within 60 days to obtain global coverage.

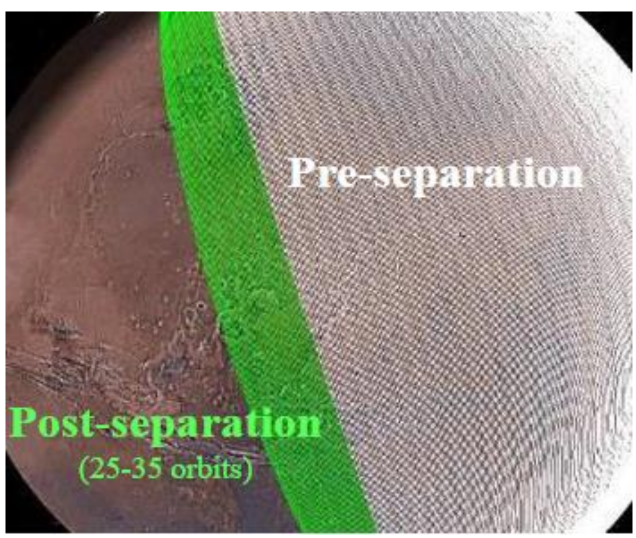

Figure 18. Pre-separation phase begins at 200 km altitude and allows natural orbit decay prior to separation at 170 km altitude.

Consequent to the number of post-separation orbits, assuming variations in drag coefficient between 2.0 and 2.2, the landing ellipse major axis may be greater than that of the circumference of Mars, shown in Figure 19. A random normal distribution of 100 drag coefficients between 2.0 and 2.2 were used for this analysis, representative of the expected range for hypersonic drag coefficient. Figure 19 illustrates the coordinates of 120 km interface provided identical separation conditions at apoapsis following the 170 km periapsis signal. Interface locations form a trend line analogous to a ground track spanning multiple orbits, demonstrating the pronounced elongation of the error ellipse major axis. In the case for $2.15 < Cd < 2.2$, the ellipse extends slightly more than a single orbit, equivalent to an ellipse major axis of > 21,000 km. The case for $2.0 < Cd < 2.2$ spans over six, equivalent to an ellipse major axis of > 128,000 km. Notable in Figure 19 is the absence of interface locations for $0° < Lat < 90°$ with $-180° < Long < 0°$ (Northwest) and $0° > Lat > -90°$ with $0° > Long > -180°$ (Southeast). This phenomenon is likely a result of the asymmetrical mass distribution of Mars. Given the regional absence of interface locations and the variability of total deorbit revolutions, a probabilistic approach is recommended to target specific landing regions unless the probe can maintain a constant *Cd* (spherical shape/no tumble).

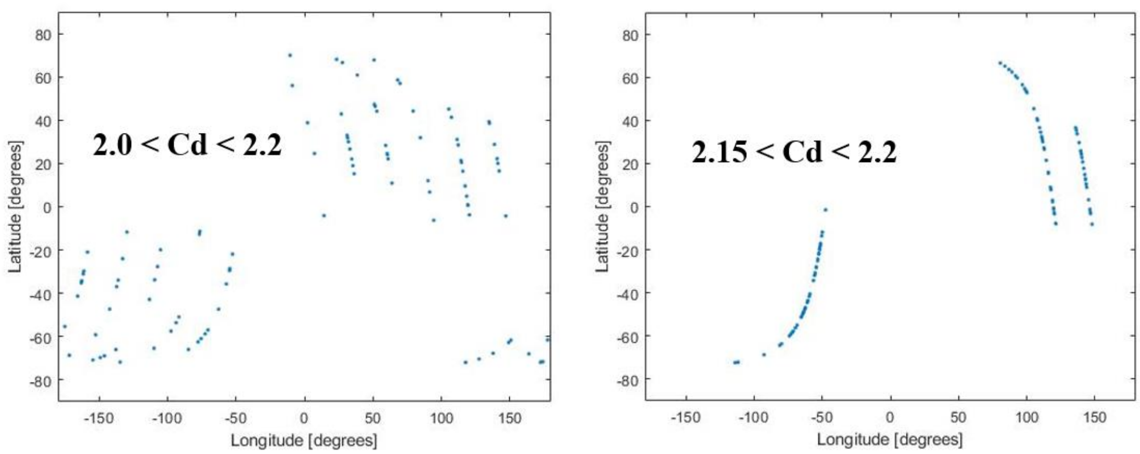

Figure 19. Geodetic locations of 120 km altitude interface resulting from 100 simulated post-separation trajectories using a randomly varied drag coefficient.

COMMUNICATION BETWEEN SURFACE PROBES AND EXISTING MARS ORBITING ASSETS

Assuming a high science data collection rate and limited probe data storage capability, a risk of data loss is presented by examining data uplink opportunities to the Aeolus orbiter. This risk can be mitigated by either upgrading hardware to increasing the uplink rate or by utilizing the existing network of Mars orbiters. The NASA JPL Horizons System[6] provides ephemeris data for the considered spacecraft network, as well as the nominal Aeolus orbit, elements of which are tabulated in Table 4. The orbits for the considered network, along with the Aeolus science orbit, are simulated in *STK/Astrogator* (Fig. 20).

Table 4. J2000 ephemeris of considered Mars-orbiting assets for communication network[6].

Spacecraft	Eccentricity	Periapsis Radius	Inclination	Longitude of Ascending Node	True Anomaly	Max Mass
MAVEN	0.363836	3604.3 km	90.82°	30.49°	351.41°	2550 kg
Mars Odyssey	0.007339	3770.7 km	69.00°	235.34°	234.83°	725 kg
Mars Reconnaissance Orbiter	0.008924	3632.4 km	101.27°	9.71°	272.80°	2180 kg
Trace Gas Orbiter	0.006822	3765.8 km	49.64°	286.45°	80.95°	4332 kg
Aeolus	0.000	3389.5 km	73.00°	0.00°	0.00°	~1800 kg

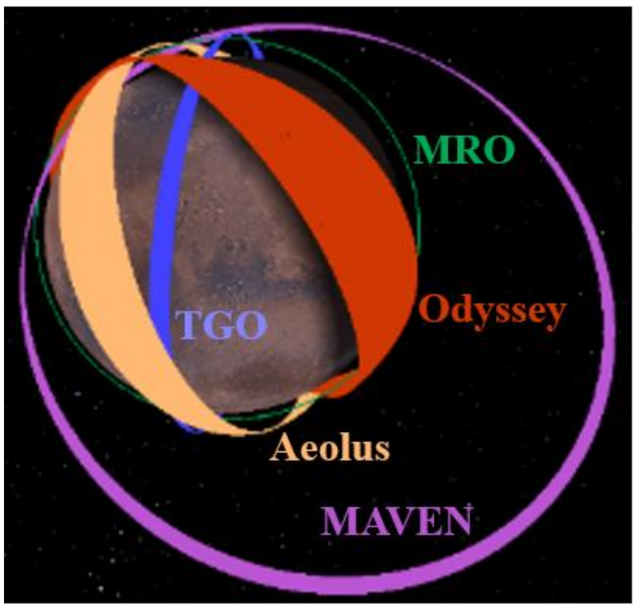

Figure 20. Representative network of Mars assets available for probe data uplink.

Each orbiter asset is propagated for 7 days, and the average data link opportunities calculated between them and a Longitudinal band between North and South poles. It is assumed that the maximum communication range for probe hardware is 1,000 km. Apart from MAVEN, available Mars assets maintain low-eccentricity orbits, therefore providing somewhat regular access duration regardless of latitude. Figure 21 compares results between the asset network and an Aeolus-only case, demonstrating comparable access durations of ~460 seconds throughout all Latitudes. The number of opportunities per day with the established network is ~5× greater. As each of the assets are held in relatively high inclinations, probes placed in polar Latitudes would encounter up to 28 revisits per day compared to 9 at the equator. Provided MAVEN’s elliptical orbit, removing the 1,000 km access constraint would provide greater average opportunity durations for probes in the Southern hemisphere.

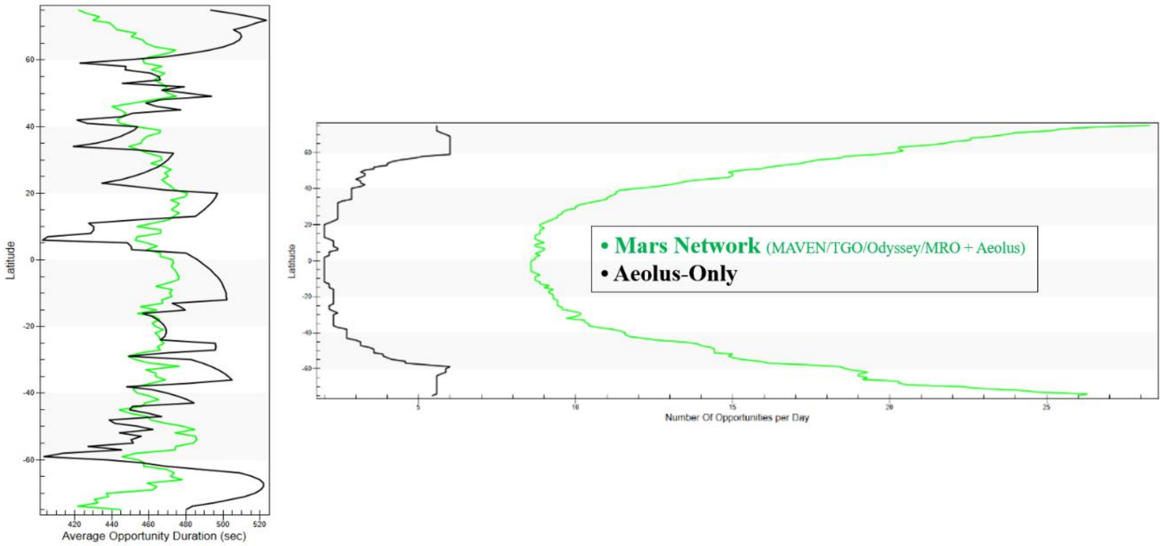

Figure 21. Number per day and duration of Mars-orbiting asset data link opportunities compared to a baseline (Aeolus only) scenario by latitude.

ALL ARCHITECTURES: DISPOSAL and PLANETARY PROTECTION

For all mission scenarios, disposal and planetary protection requirements are met by ensuring a minimum lifetime of 50 years in Mars orbit. Fortunately, the science orbit with parameters of 400 km altitude (initially $e = 0$) and 73-degree inclination is a quasi-frozen orbit which is stable for at least 50 years. Specifically, the argument of periapsis and eccentricity are bounded (Fig. 22), as well as the altitude which oscillates between ~350 and ~450 km over a 50-year timespan (Fig. 23). Of note is the Mars Odyssey spacecraft is orbiting Mars in a similar orbit, for over 20 years as of the time of this writing[7].

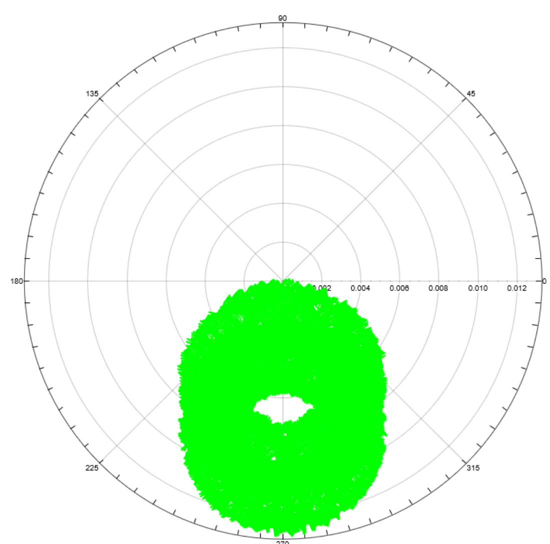

Figure 22. Polar plot of eccentricity vs. argument of periapsis for disposal orbit over 50-year timespan, which results naturally from the science orbit of 400 km altitude and 73-degree inclination.

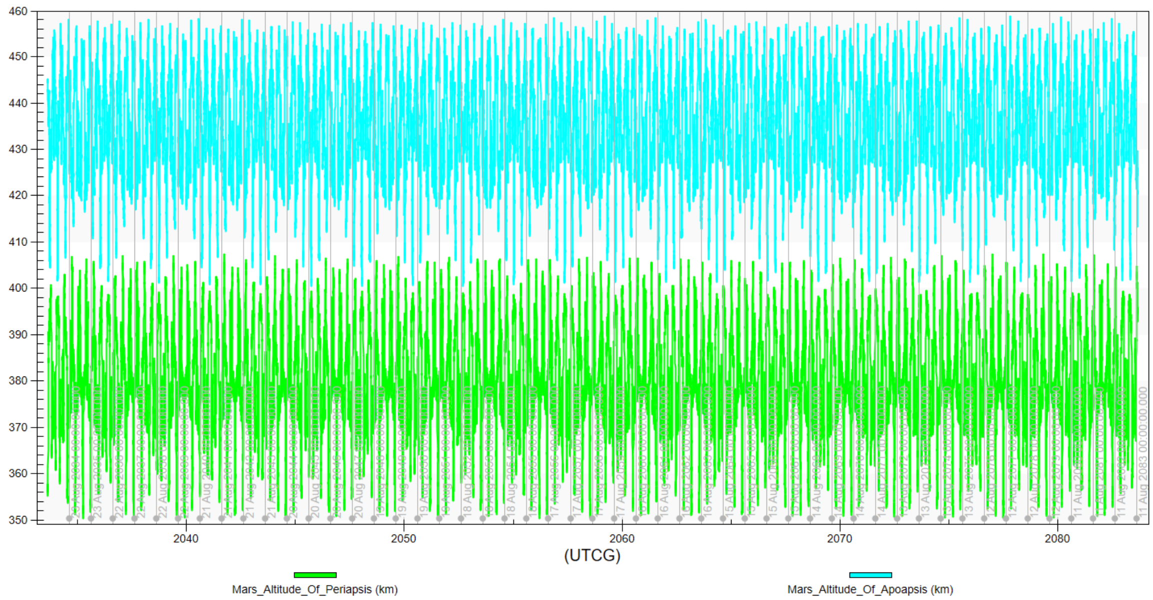

Figure 23. Disposal orbit altitude (both periapsis and apoapsis) oscillation over 50-year timespan.

SUMMARY and FUTURE WORK

Preliminary trajectory analysis and feasibility assessments were performed for 24 distinct trajectory options among the scenarios seen in Appendices B and C, complete with ΔV budgets and mission duration information. Notably, global surface coverage was achieved via probe deployment during hyperbolic approach (i.e., Architecture 1), although there were northern latitude limits in the presented nominal case due to Mars' axial tilt pointed towards the approach asymptote. However, combining *Architectures 1* and 2 yields a powerful hybrid architecture capable of targeting the full range of latitude and longitude on the Martian surface; thus, *Option 17* was selected from *Hybrid Architecture 1 & 2* as the nominal case to be studied in more detail. Specifically, future work will focus on probe surface distribution and dispersions trades to determine landing error ellipses which may impact operations. Probe power generation systems will also be investigated to determine proximity constraints to frost and operation in shadow based on L_s and landing site latitude. Finally, given the early stages of this concept, more aerobraking trades are to be performed due to the evolving wet mass of the spacecraft design.

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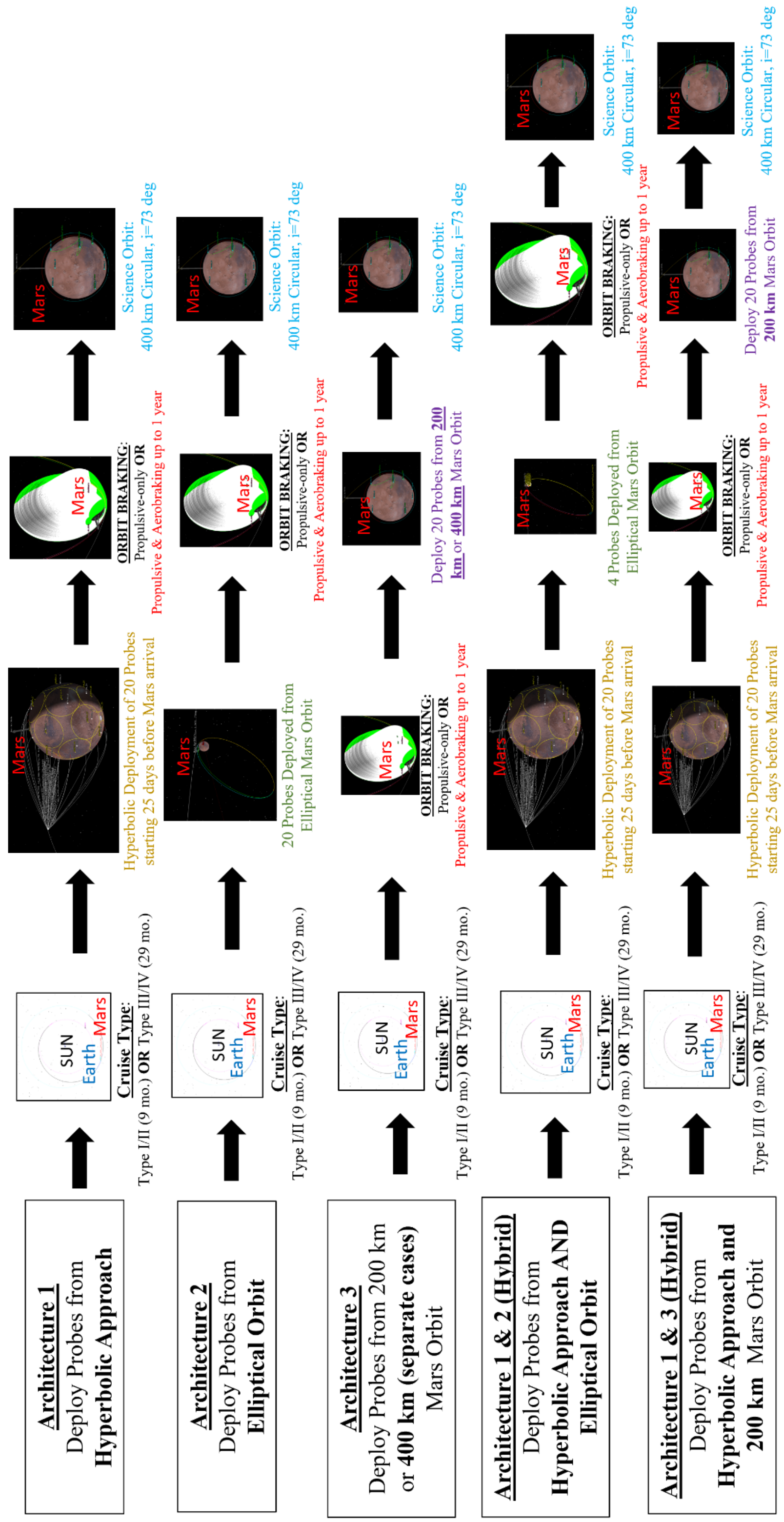
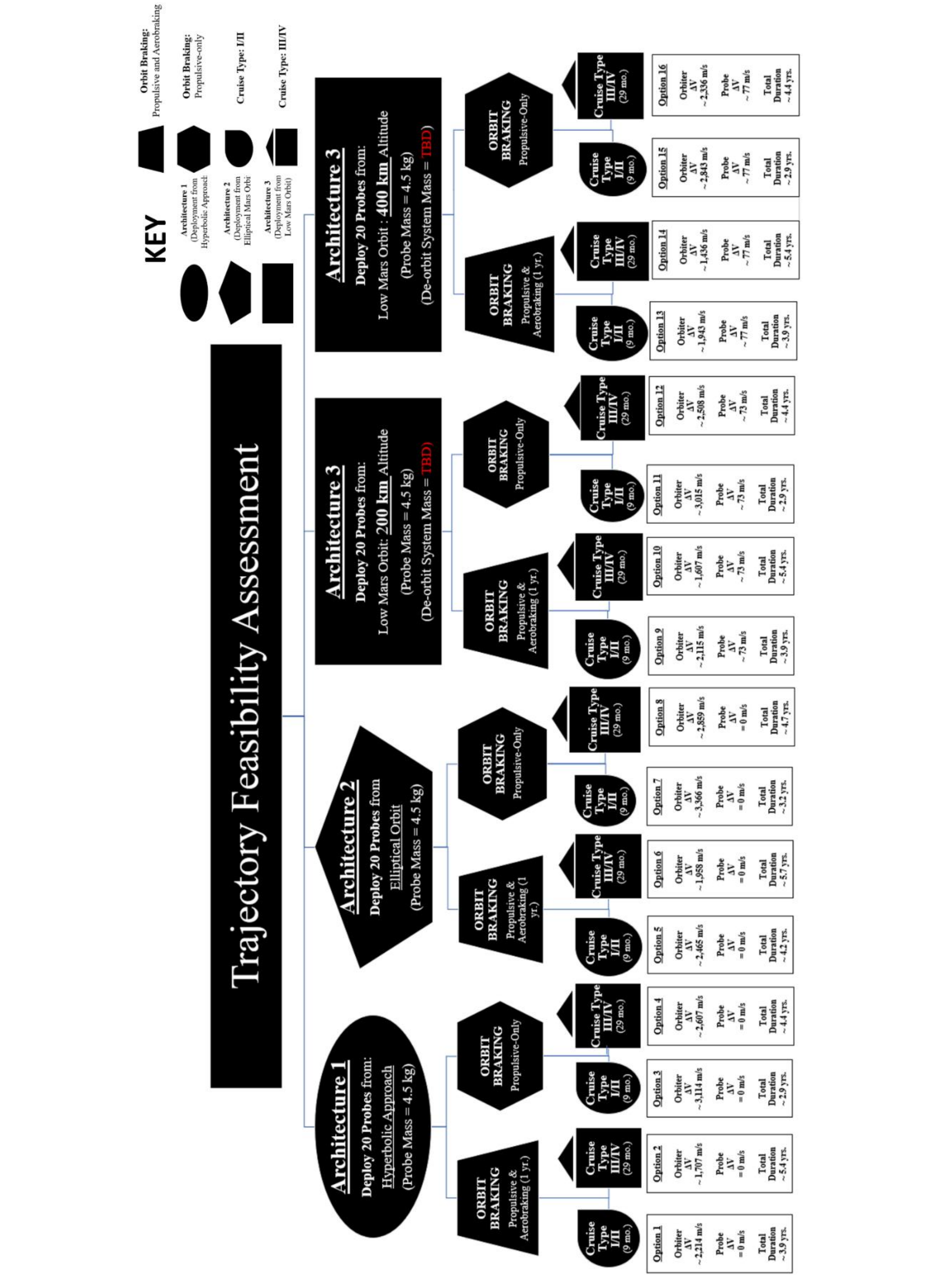
APPENDIX A: VARIATION IN CONCEPT of OPERATIONS



APPENDIX B: TRAJECTORY FEASIBILITY ASSESSMENT (Architectures 1, 2, and 3)



APPENDIX C: TRAJECTORY FEASIBILITY ASSESSMENT (Hybrid Architectures)